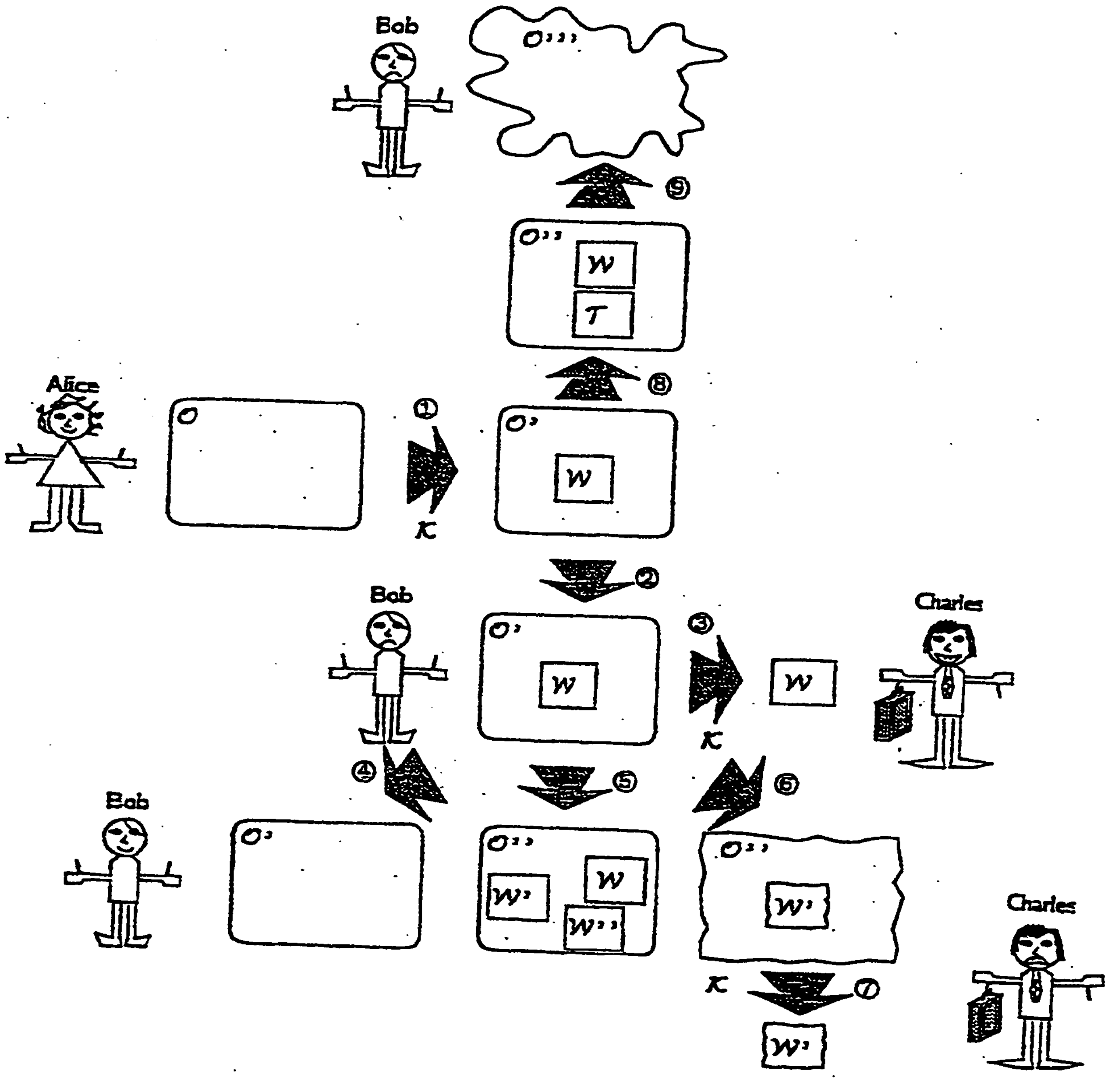

FIGURE 1

Figure 1: At ① Alice adds a watermark $\mathcal{W}$ using key $\mathcal{K}$ to her object $\mathcal{O}$ to make $\mathcal{O}'$. At ② Bob steals a copy of $\mathcal{O}'$. At ③ Charles extracts the watermark from $\mathcal{O}'$ using the key $\mathcal{K}$ to show that $\mathcal{O}'$ is owned by Alice. At ④ Bob successfully removes $\mathcal{W}$ from $\mathcal{O}$. At ⑤ Bob adds new watermarks $\mathcal{W}'$ and $\mathcal{W}''$ to make it hard for Charles to prove that $\mathcal{W}$ is Alice's original watermark. At ⑥ Bob distorts $\mathcal{O}'$ (and $\mathcal{W}$) making it difficult for Charles to detect $\mathcal{W}$. At ⑦ Charles attempts to extract the watermark from the distorted object, and either fails completely or gets a distorted watermark. At ⑧ Alice adds tamperproofing $\mathcal{T}$ to $\mathcal{O}$. At ⑨ Bob tries to remove $\mathcal{W}$ from $\mathcal{O}$, but, due to the tamperproofing, $\mathcal{O}$ will be rendered useless to Bob.

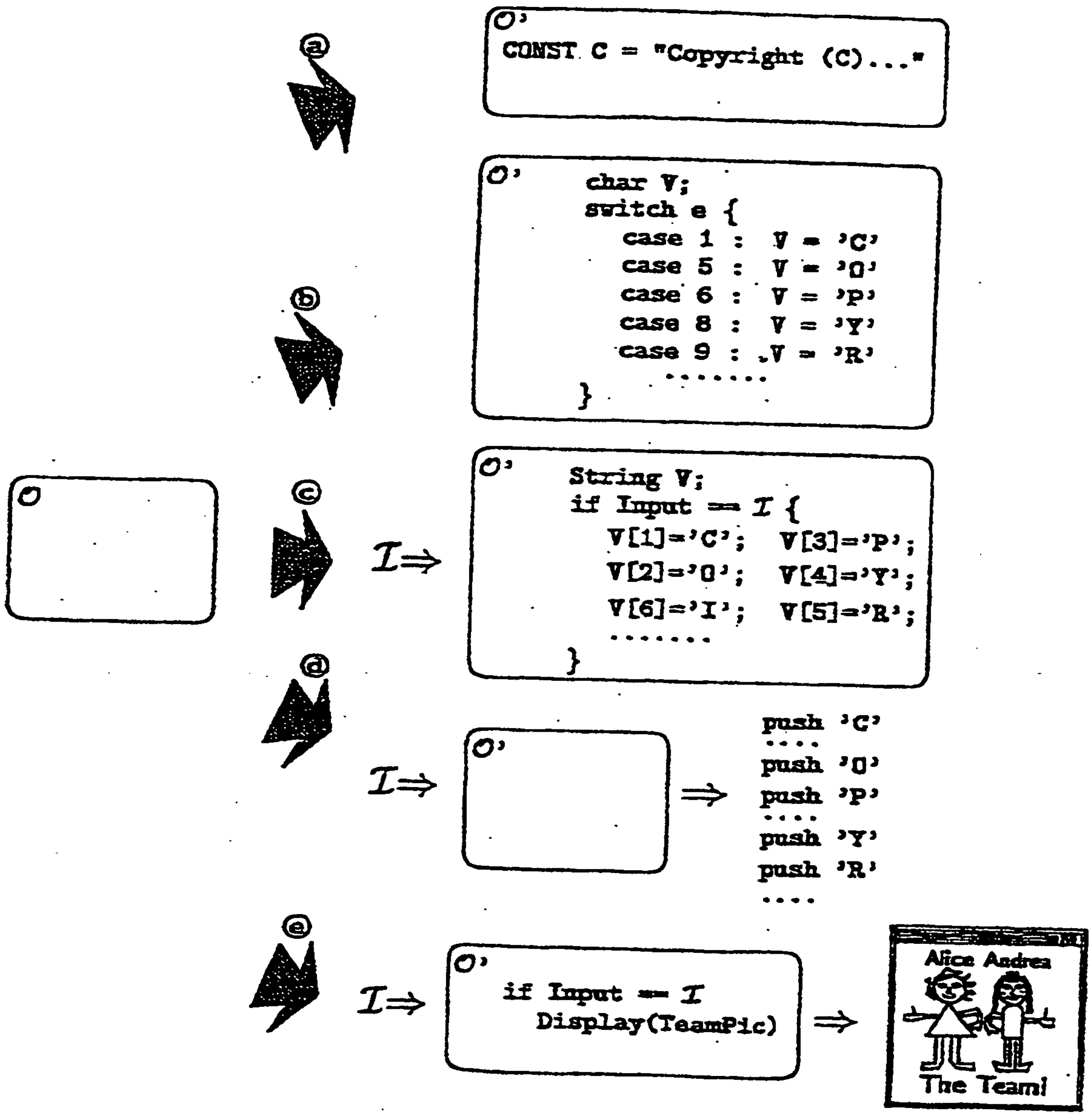

FIGURE 2

Figure 2: In ⓐ Alice embeds a watermark in the initialized data (string) section of her program. In ⓑ the watermark is embedded in the text (code) section of the program. In ⓒ the watermark gets embedded in a global variable V when the program is run with input $\mathcal{I}$. In ⓓ the watermark is embedded in the execution trace when the program is run with input $\mathcal{I}$. In ⓔ the watermark is embedded in the unexpected behavior (an "Easter Egg") of the program when it is run with input $\mathcal{I}$.

```
String G (int n) {
   int i=0,k;
   String S;
   while (1) {
      L1:  if (n==1) {S[i++]="A";k=0;goto L6};
      L2:  if (n==2) {S[i++]="B";k=-2;goto L6};
      L3:  if (n==3) {S[i++]="C";goto L9};
      L4:  if (n==4) {S[i++]="X";goto L9};
      L5:  if (n==5) {S[i++]="C";goto L11};
            if (n>12) goto L1;
      L6:  if (k++<=2) {S[i++]="A";goto L6} else goto L8;
      L8:  return S;
      L9:  S[i++]="C"; goto L10;
      L10:  S[i++]="B"; goto L8;
      L11:  S[i++]="C"; goto L12;
      L12:  goto L10;
   }
}
```

FIGURE 3

Figure 3: A function producing the the strings "AAA", "BAAAA", "XCB", and "CCB".

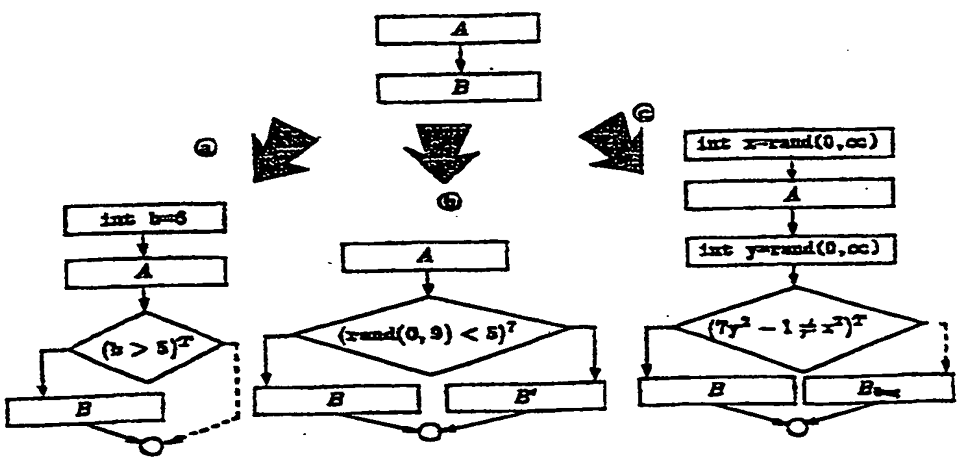

FIGURE 4

Figure 4: Inserting bogus predicates in a program. In ⓐ an opaque predicate $b > 5^T$ is inserted. This predicate is always true. In ⓑ an opaque predicate $rand(0, 9) < 5^?$ is inserted. This predicate is sometimes true (in which case B is executed), and sometimes false (in which case an obfuscated version of B is executed). In ⓒ an opaque true predicate is inserted. This predicate appears to sometimes execute an obfuscated buggy version of B, but, in fact, never does.

$g(V)$ p	q	$f(p,q)$ V	$2p+q$
0	0	False	0
0	1	True	1
1	0	True	2
1	1	False	3

	AND[A,B]	A: 0	1	2	3
B	0	3	0	0	0
	1	3	1	2	3
	2	0	2	1	3
	3	3	0	0	3

```
(1) bool A,B,C;                (1') short a1,a2,b1,b2,c1,c2;
(2) B = False;                 (2') b1=0; b2=0;
(3) C = False;        T        (3') c1=1; c2=1;
(4) C = A & B;       ==>       (4') x=AND[2*a1+a2,2*b1+b2]; c1=x/2; c2=x%2;
(5) C = A & B;                 (5') c1=(a1 ^ a2) & (b1 ^ b2); c2=0;
(6) if (A) ...;                (6') x=2*a1+a2; if ((x==1) || (x==2)) ...;
(7) if (B) ...;                (7') if (b1 ^ b2) ...;
```

FIGURE 5

Figure 5: Variable splitting example. We show one possible choice of representation for split boolean variables. The table indicates that boolean variable V has been split into two short integer variables p and q. If $p = q = 0$ or $p = q = 1$ then V is False, otherwise, V is True. Given this new representation, we devise substitutions for the built-in boolean operations. In the example, we provide a run-time lookup table for each operator. Given two boolean variables $V_1 = [p, q]$ and $V_2 = [r, s]$, $\ulcorner V_1 \& V_2 \urcorner$ is computed as $\ulcorner \mathrm{AND}[2p+q, 2r+s] \urcorner$.

$$
\begin{aligned}
Z(X+r,Y) &= 2^{32}\cdot Y+(r+X) &&= Z(X,Y)+r\\
Z(X,Y+r) &= 2^{32}\cdot(Y+r)+X &&= Z(X,Y)+r\cdot 2^{32}\\
Z(X\cdot r,Y) &= 2^{32}\cdot Y+X\cdot r &&= Z(X,Y)+(r-1)\cdot X\\
Z(X,Y\cdot r) &= 2^{32}\cdot Y\cdot r+X &&= Z(X,Y)+(r-1)\cdot 2^{32}\cdot Y
\end{aligned}
$$

```
(1) int X=45;                  (1') long Z=167759086119551045;
    int Y=95;
(2) X += 5;           T        (2') Z += 5;
(3) Y += 11;         ==>       (3') Z += 47244640256;
(4) X *= c;                    (4') Z += (c-1)*(Z & 4294967295);
(5) Y *= d;                    (5') Z += (d-1)*(Z & 18446744069414584320);
```

FIGURE 6

Figure 6: Merging two 32-bit variables X and Y into one 64-bit variable Z. Y occupies the top 32 bits of Z, X the bottom 32 bits. If the actual range of either X or Y can be deduced from the program, less intuitive merges could be used. First we give rules for addition and multiplication with X and Y, then show some simple examples.

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```
int Sum(int A[]) {
  int i, sum=0;
  int n=A.length;
  for (i=0;i<n;i++)
    sum += A[i];
  return sum;
}
```

$\xrightarrow{T}$

```
int Sum(int A[]) {
  int sum=0, i=0, pc=0;
  int s[]=new int[5], sp=-1;
  loop:  while (true)
    switch("fcgabced".charAt(pc)) {
      case 'a':  sum += s[sp--]; pc++; break;
      case 'b':  i++; pc++; break;
      case 'c':  s[++sp] = i; pc++; break;
      case 'd':  if (s[sp--] > s[sp--]) pc -= 6;
                 else break loop; break;
      case 'e':  s[++sp] = A.length; pc++; break;
      case 'f':  pc += 5; break;
      case 'g':  s[sp] = A[s[sp]]; pc++; break;
    }
  return sum;
}
```

FIGURE 7

Figure 7: The Java method Sum on the left is obfuscated by translating it into the bytecode "fcgabced". This code is then executed by a stack-based interpreter specialized to handle this particular virtual machine code. This technique is similar to Proebsting's superoperators [20].

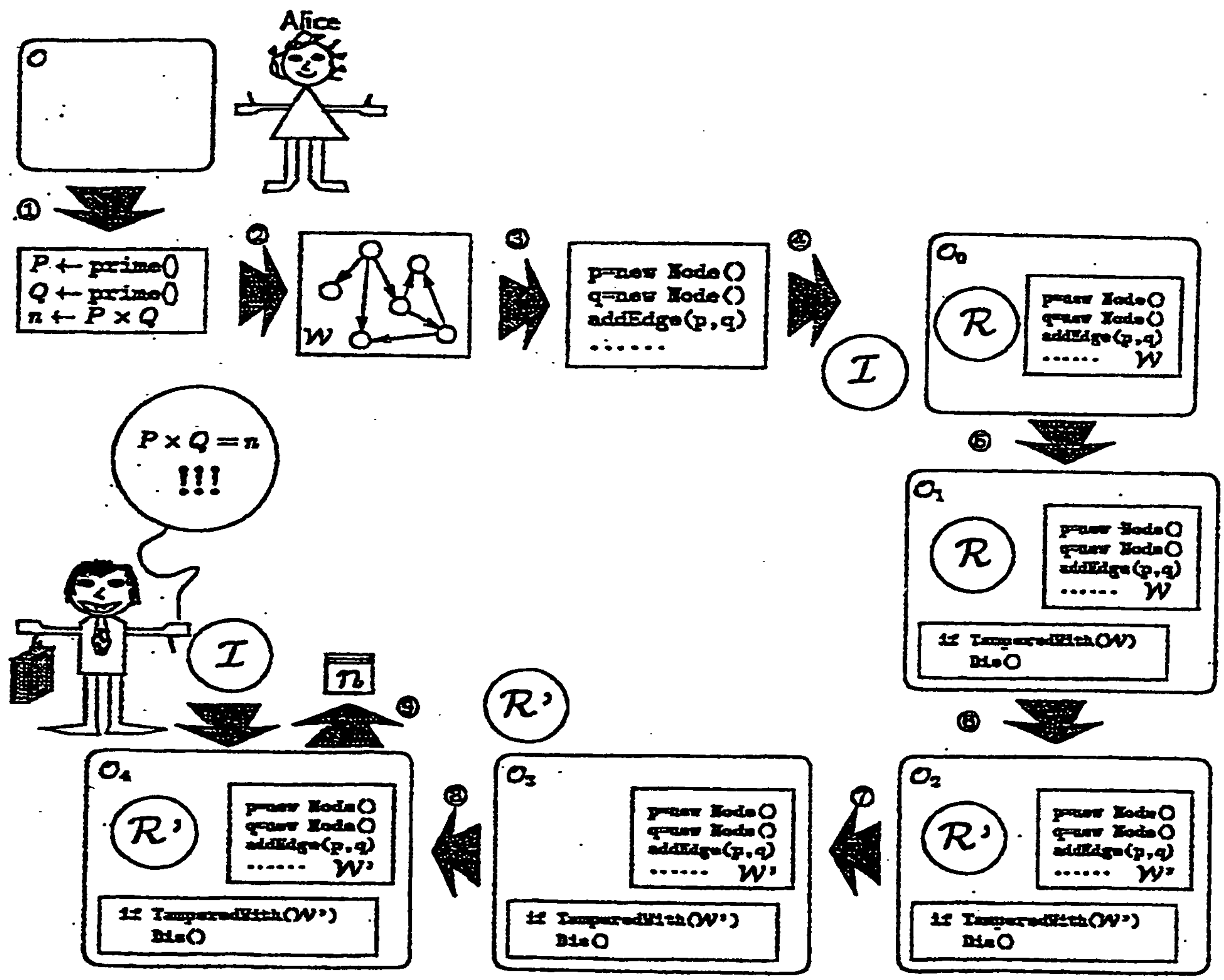

FIGURE 8

Figure 8: At ① Alice selects two large primes P and Q, and computes their product n. At ② she embeds n in the topology of a graph. This graph is her watermark $\mathcal{W}$. At ③ $\mathcal{W}$ is converted to a program which builds the graph. At ④ the program is embedded into the original program $\mathcal{O}$, such that when $\mathcal{O}_0$ is run with $\mathcal{I}$ as input, $\mathcal{W}$ is built. Also, a recognizer program $\mathcal{R}$ is constructed, which is able to identify $\mathcal{W}$ on the heap, and extract n from it. At ⑤ tamperproofing is added, to prevent the graph from being obfuscated to such an extent that $\mathcal{R}$ cannot identify it. At ⑥ the application (including the watermark, tamperproofing code, and recognizer) is obfuscated. At ⑦ the recognizer is removed from the application. $\mathcal{O}_3$ is the version of Alice's program that is distributed. At ⑧ Charles links in the recogniser program $\mathcal{R}$ with $\mathcal{O}_3$. At ⑨ the application is run with $\mathcal{I}$ as input, and the recogniser $\mathcal{R}$ produces n. Since Charles is the only one who can factor n, he can prove the legal origin of Alice's program.

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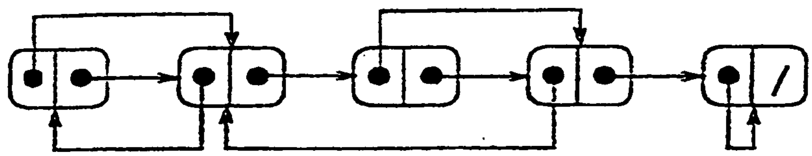

$3 \cdot 6^4 \quad + \quad 2 \cdot 6^3 \quad + \quad 3 \cdot 6^2 \quad + \quad 4 \cdot 6^1 \quad + \quad 1 \cdot 6^0 = 4453 = 61 * 73$

FIGURE 9

Figure 9: Embedding a watermark into a graph structure. The structure is essentially a linked list. The rightmost pointer of each node is the next field, while the second field encodes a digit. In this example, 0=null (/), 1=a self-pointer, 2=a one-step back pointer, 3=a one step forward pointer, 4=a two step back pointer, and 5=a 2 step forward pointer. This allows us to encode a value $61 * 73 = 4453_{10}$ as the base-6 value 32341_6.

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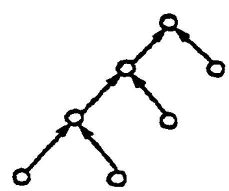

FIGURE 10

Figure 10: The twenty-second tree in an enumeration of the oriented trees with seven vertices.

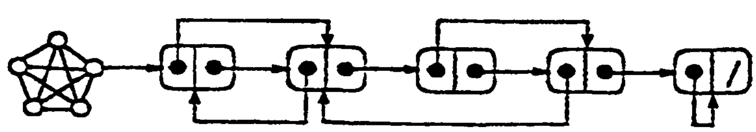

FIGURE 11

Figure 11: A 5-clique is used to mark the beginning of an encoded value.

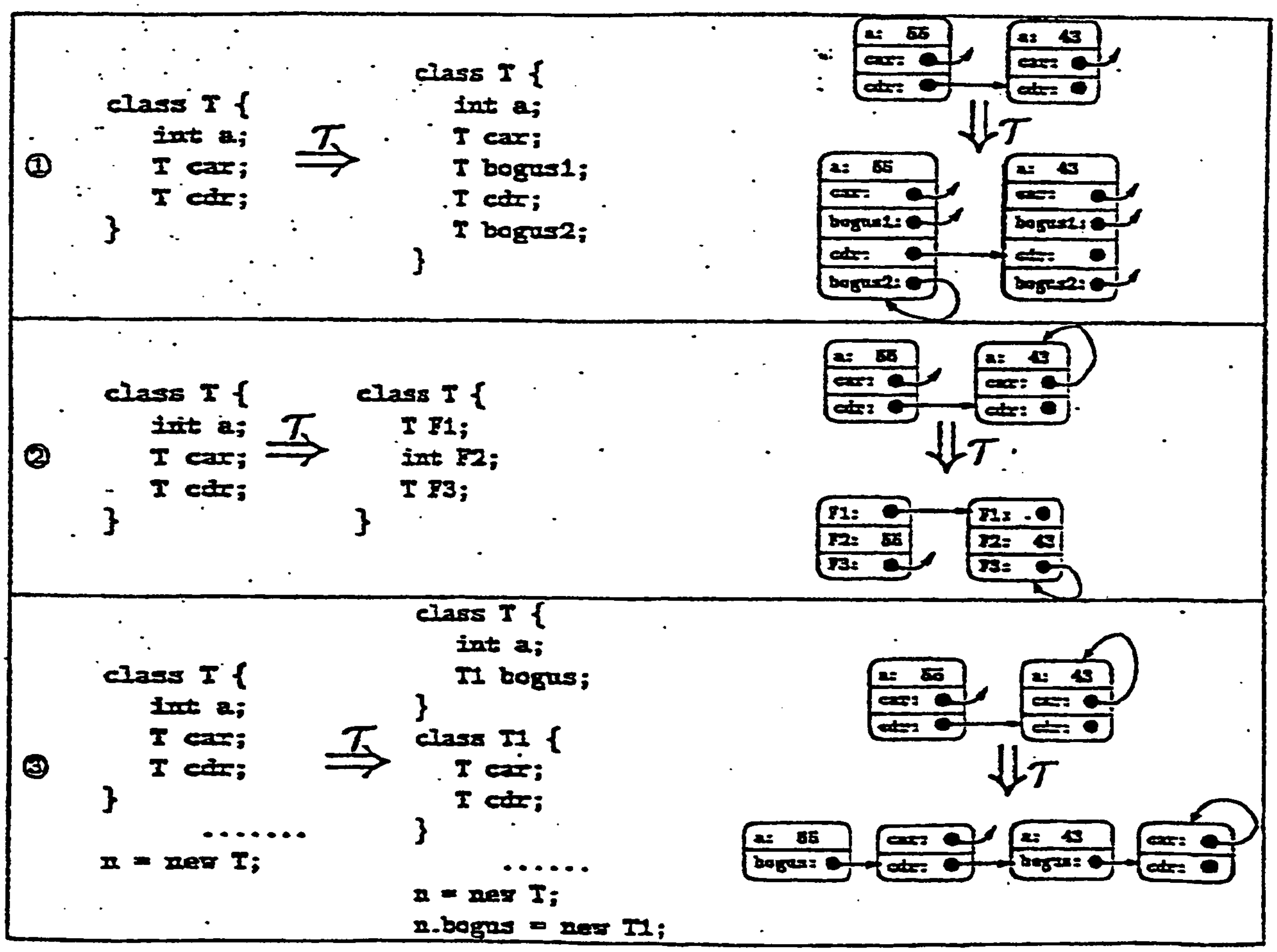

FIGURE 12

Figure 12: Obfuscation of dynamic structures. In ① we add bogus pointer fields to all nodes of type T. In ② we rename and reorder fields. In ③ we add a level of indirection by splitting all nodes in two.

```
class C {public int a; public C car, cdr;}

public static void main(String[] args) {
   Field[] F = C.class.getFields();
   if (F.length != 3)
      die();
   if (F[0].getType() !=
      java.lang.Integer.TYPE)
      die();
   if (F[1].getType() != C.class)
      die();
   if (F[2].getType() != C.class)
      die();
}
```

(a)

```
class C {public int a; public C car, cdr;}

public static void main(String[] args)
      throws NoSuchFieldException,
      IllegalAccessException {
   Field f;
   String V;
   C n = new C();
   Class c = n.getClass();
   if (P^F) {
      f = c.getField(V=="car");
      ① f.set(n, null);
   }

   Field F = c.getFields();
   int R;
   ② F[R==1].set(n, n.car);
}
```

(b)

FIGURE 13

Figure 13: Examples of tamperproofing Java code using the reflection interface.

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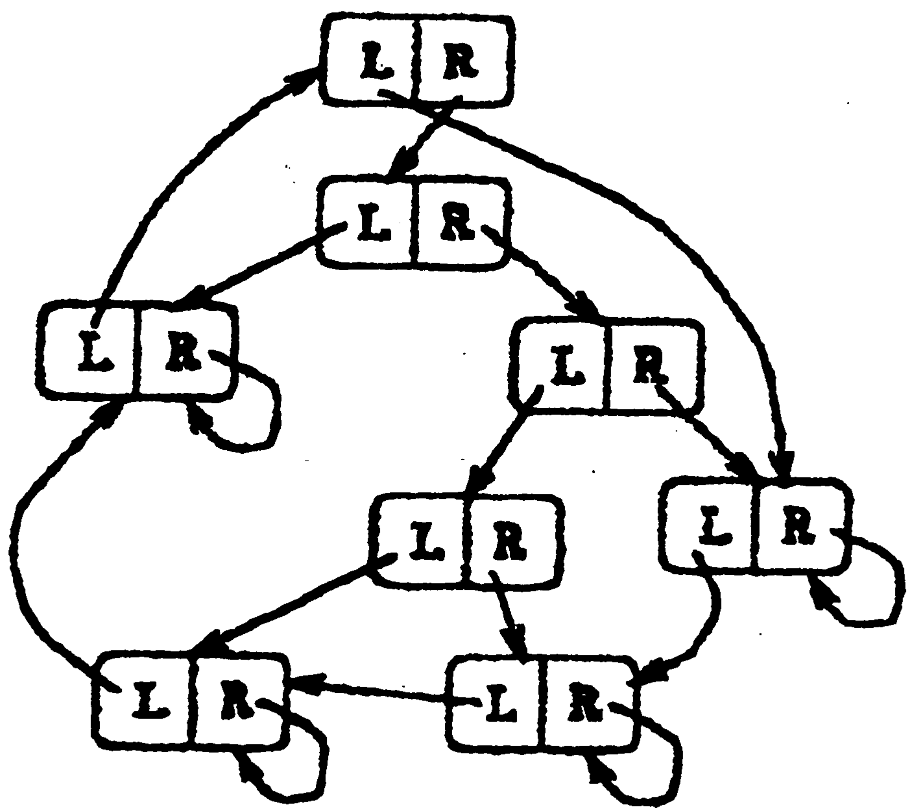

FIG 14

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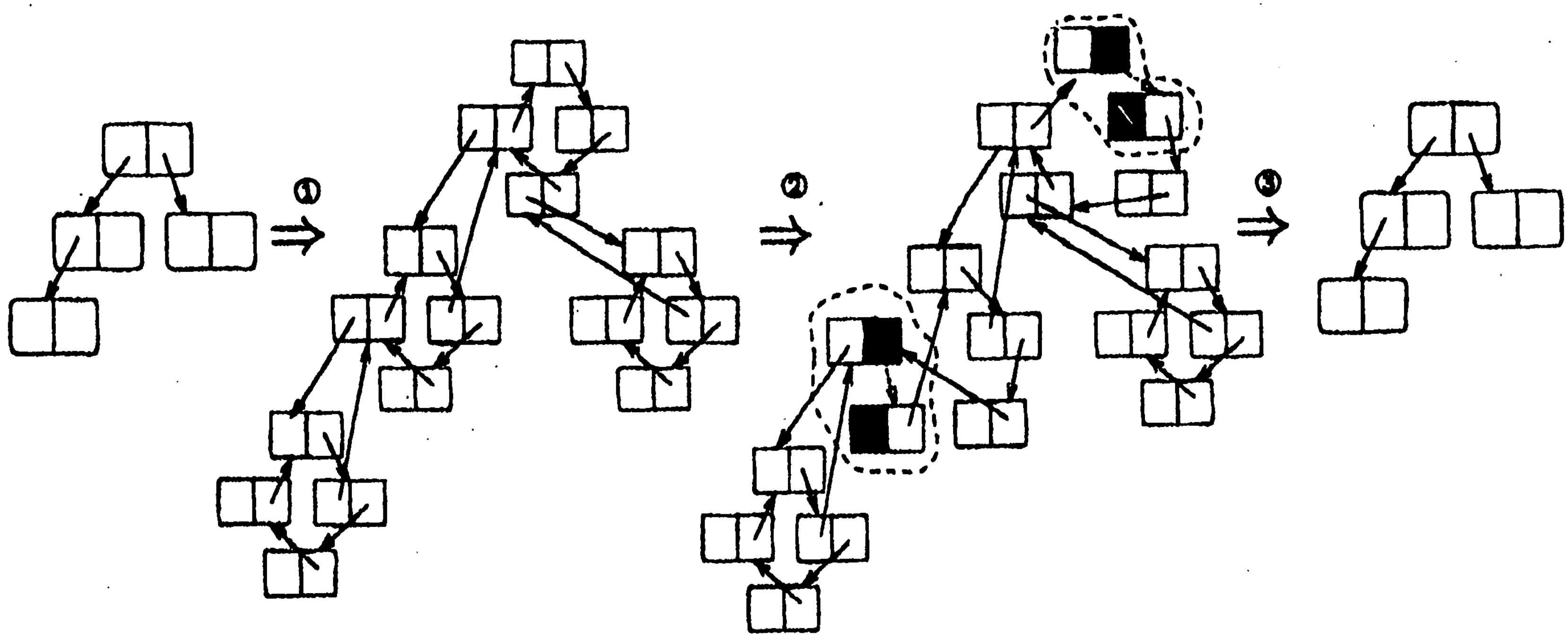

Figure 15 Tamperproofing against node-splitting. At ① we expand each node of our original watermark tree into a 4-cycle. At ② an adversary splits two nodes. The structure of the graph ensures that these nodes will fall on a cycle. At ③ the recognizer shrinks the biconnected components of the underlying (undirected) graph. The result is a graph isomorphic to our original watermark.

FIG 15